Roadmap for the next 25 minutes

• CASMO5 lattice physics code development
  – New libraries, e.g. ENDF/B-VII.1 and JENDL-4.0
  – New numerical models, e.g. linear source model

• Motivation for development new data libraries

• General comments on the E7R1 and JENDL-4.0 evaluations and libraries

• Results for the C5G7 MOX benchmark and some other MxN problems

• Results for some critical experiments with new libraries and linear source
  – B&W 1810 Series
CASMO5 – Pieces and Parts of a Lattice Physics Code (circa 2010):

- Library: ENDF/B-VII.0 586 group nuclear data library

- Resonance Calculation: Equivalence Theory based with characteristics based Dancoff calculation

- 2D Transport Solution: Method of Characteristics (flat source)

- Depletion solver: Linear chains with Predictor/Corrector depletion (with special quadratic Gd depletion)
CASMO5 – Pieces and Parts of a Lattice Physics Code (circa 2012)
-A lot has changed:

• Library: ENDF/B-VII.1 586 group nuclear data library

• Resonance Calculation: Equivalence Theory based with characteristics based Dancoff calculation (the same)

• 2D Transport Solution: Method of Characteristics (linear source)

• Depletion Solver: 4th order Runge-Kutta-Fehlberg (RKF) (under very near term development)
New Nuclear Data → New Opportunities!

Truly state-of-the-art nuclear data:

- JENDL-4.0 (Released May 2010)
- ENDF/B-VII.1 (Released Dec. 22, 2011)

New data on the libraries allows the implementation of new models not possible with the old data libraries.
# Quick CASMO Library Comparison

<table>
<thead>
<tr>
<th></th>
<th>CASMO4 L-Library</th>
<th>CASMO5 E7R0 (old)</th>
<th>CASMO5 E7R1/J4/J311 (new)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaluation</td>
<td>E4</td>
<td>E7R0</td>
<td>E7R1/J4.0/J311</td>
</tr>
<tr>
<td># Neutron Grps</td>
<td>70</td>
<td>586</td>
<td>586</td>
</tr>
<tr>
<td># Thermal Grps</td>
<td>43 (&lt;0.4 eV)</td>
<td>42 (&lt; 0.625 eV)</td>
<td>42 (&lt; 0.625 eV)</td>
</tr>
<tr>
<td># Gamma Grps</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>#IDs (nuclide/materials)</td>
<td>103</td>
<td>454</td>
<td>568 [+114]</td>
</tr>
<tr>
<td># Actinides</td>
<td>19</td>
<td>51</td>
<td>60</td>
</tr>
<tr>
<td># Fission Products</td>
<td>29 + 2 Lumps</td>
<td>234</td>
<td>259 [+25]</td>
</tr>
<tr>
<td># Resonance isotopes</td>
<td>21</td>
<td>136</td>
<td>232 [+96]</td>
</tr>
<tr>
<td># with Pn-data</td>
<td>---</td>
<td>66</td>
<td>106 [+40]</td>
</tr>
<tr>
<td># Nuclides with N,2N etc.</td>
<td>N,2N (4)</td>
<td>N,2N (178)</td>
<td>N,2N (396), N,3N (347) N,4N (32)</td>
</tr>
</tbody>
</table>
Explicit Shielding of Low Energy Resonances

Pu239, Pu240, U235, U238
6.67, 20.87, 36.7 eV

Fine groups
Shielded

Cross Section (b)

Incident Energy (eV)
Components of a CASMO5 Library

- Multigroup microscopic cross section data for: $\sigma_a$, $\sigma_f$, $\nu\sigma_f$, and $\sigma_{tr}$ and $P_0$ scattering matrices (incl. $S(\alpha,B)$ data)
- Resonance data (shielding data tabulated at 18 background cross sections and up to 10 temperatures spanning 293K to 2700K)
- Resonance upscatter data and Goldstein-Lambda values
- Prompt and delayed neutron fission spectra
- Delayed neutron data ($\beta$’s, $\lambda$’s and delayed neutron emission spectra)
- Pn-scattering data (up to order 5 for nuclides where anisotropic scattering is important)
- $(n,2n)$, $(n,3n)$ and $(n,4n)$ data
- Fission yield and radioactive decay data and energy release per fission data
General comments JENDL-4.0 library:

All new minor actinide data

No new fission yields or decay sub-library for J4.0
(*CASMO* J4.0 library uses E7R1 fission yield/decay data)

Gd-157 data different from E7R1 or (taken from recent RPI measurements)

Includes data for Osmium and Ytterbium
General comments E7R1 library:

E7R1 contains new evaluations for:

\[ ^{27}\text{Al}, ^{52}\text{Cr}, ^{53}\text{Cr}, ^{55}\text{Mn}, ^{58}\text{Ni}, ^{60}\text{Ni}, ^{78}\text{Kr}, ^{90}\text{Zr}, ^{123}\text{Xe}, ^{124}\text{Xe}, ^{180}\text{W}, ^{182}\text{W}, ^{183}\text{W}, ^{184}\text{W}, ^{186}\text{W}, ^{185}\text{Re}, ^{237}\text{U}, ^{239}\text{U}, ^{240}\text{Pu}, ^{240}\text{Am}, ^{174}\text{Hf}, ^{176}\text{Hf}, ^{177}\text{Hf}, ^{178}\text{Hf}, ^{179}\text{Hf}, \text{and} ^{180}\text{Hf} \]

All new minor actinide data in the evaluation from JENDL 4.0

New fission yields and decay sub-library

Delayed neutron data rolled back to E6R8 release

Final release included some Tm data, no Os data

Both libraries now allow direct calculation with enriched boron
Upgraded Thorium chains

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Extension of the Berklium chain

(By default **CASMO5** generates all the isotopics for the **SNF** (Spent Nuclear Fuel) code)
CASMO-4 L-Library

Very simple heavy metal chains – all the essentials but too simplified to work with the SNF code

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Also enhanced Gd residual...

Addition of the Dy/Ho fission product chain

**CASMO5** - no lumped fission product!
Tungsten/Rhenium and Osmium Data

• The new libraries now have tungsten, rhenium, and osmium data as burnable absorbers:

Motivation: for depletion of AP1000 control rods (where buildup of Re-187 is important)

• Now modeled in SIMULATE5
Ytterbium and Thulium data allows for extension of the Erbium depletion chain

and Hf-175 been added to the Hf chain:
New 2D transport Solver: Motivation

• Current transport solver based on Flat Source (FS) Method of Characteristics

• Certain problems require very fine flat source mesh to achieve desired accuracy
  – C5G7 MOX benchmark reflector region

• Mesh refinement → Increase number of tracks
  – Run time and storage can greatly increase
• For some regions it is not so easy to refine the flat source mesh, so instead of spatial refinement, improve spatial source ‘shape’
  – Assume source is linear function of space

• Goal: By using a higher order method we can eliminate the need for excessive flat source mesh in the problem

⇒ CASMO5 Linear Source Model ~3 years in development
C5G7 MOX Benchmark

• C5G7 MOX benchmark previously solved with Flat Source MoC in CASMO5 (2008 ANS Winter Meeting)
  – Good accuracy (~ 5-10 pcm error, < 0.04 max. pin power error)
  – Good performance (~8 min. run time)
  – Very fine flat source spatial discretization required
C5G7 MOX Benchmark

- Four 17x17 UO$_2$ and MOX assemblies surrounded by water reflector region with fixed cross sections (7 group)

Very tough problem – gold standard for testing transport solvers
CASMO5 MxN Model with Refined FSR

- Refined FSR
  - 5 rings inside a fuel pin
  - 10 rings in coolant region
  - $1/16^{th}$ division in azimuthal
  - 0.1 cm x 0.1 cm in reflector
  - Number of FSR: 416,168
CASMO5 Discretization

Fine Mesh

Coarse Mesh
# Solutions to the C5G7 Benchmark

<table>
<thead>
<tr>
<th>Code</th>
<th>Method</th>
<th>k-eff</th>
<th>Pin Power max</th>
<th>Pin Power min</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCNP (ref)</td>
<td>MC</td>
<td>1.18655</td>
<td>2.498</td>
<td>0.232</td>
</tr>
<tr>
<td>CASMO (fine mesh)</td>
<td>MOC</td>
<td>1.18660</td>
<td>2.497</td>
<td>0.233</td>
</tr>
<tr>
<td>CASMO (default)</td>
<td>MOC</td>
<td>1.18632</td>
<td>2.488</td>
<td>0.237</td>
</tr>
<tr>
<td>CRX</td>
<td>MOC</td>
<td>1.18813</td>
<td>2.498</td>
<td>0.233</td>
</tr>
<tr>
<td>APOLLO2</td>
<td>MOC</td>
<td>1.18634</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LANCER02</td>
<td>MOC</td>
<td>1.18660</td>
<td>2.498</td>
<td>0.23</td>
</tr>
<tr>
<td>HELIOS</td>
<td>CCCP</td>
<td>1.19330</td>
<td>2.545</td>
<td></td>
</tr>
<tr>
<td>CRONOS</td>
<td>S8</td>
<td>1.18338</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATTLILA</td>
<td>S16</td>
<td>1.18658</td>
<td>2.494</td>
<td>0.231</td>
</tr>
<tr>
<td>PENTRAN</td>
<td>S16</td>
<td>1.18760</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PARTISN</td>
<td>S40</td>
<td>1.18632</td>
<td>2.503</td>
<td>0.232</td>
</tr>
<tr>
<td>VARIANT</td>
<td>P5</td>
<td>1.19181</td>
<td>2.535</td>
<td></td>
</tr>
</tbody>
</table>

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CASMO5 Pin Fission Rate Distribution (fine mesh)

- Maximum error is 0.7 % at the corner pin. RMS error 0.2%
- Higher error in the interfaces with water reflectors.
- Fine FSR in water reflectors is important for accurate pin powers in the periphery.
New C5 Results for C5G7 Benchmark

<table>
<thead>
<tr>
<th>Source</th>
<th>Mesh</th>
<th>K-eff Error (pcm)</th>
<th>Max. Power Error (%)</th>
<th>Min. Power Error (%)</th>
<th>Memory (Rel.)</th>
<th>Run time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS</td>
<td>Coarse</td>
<td>56.6</td>
<td>-0.769</td>
<td>3.879</td>
<td>1</td>
<td>82.2</td>
</tr>
<tr>
<td>LS</td>
<td>Coarse</td>
<td>-2.9</td>
<td>0.024</td>
<td>0.298</td>
<td>1.01</td>
<td>121.5</td>
</tr>
<tr>
<td>FS</td>
<td>Fine</td>
<td>10.2</td>
<td>-0.036</td>
<td>0.598</td>
<td>11.44</td>
<td>487.8</td>
</tr>
</tbody>
</table>

- Results compared to MCNP reference solution
- Performed calculation with **FS** on **fine** and **coarse** grid and **LS** on **coarse** grid
- All cases converged in 8 transport sweeps
C5G7 Pin Power Percent Error - Hybrid

FS-All

LS-Reflector

LS-Fuel

LS-All

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CASMO5 Fictitious MxN BWR Model

Flat Source k-eff: 0.83931

Linear Source k-eff: 0.84163

232 pcm delta
CASMO5 Fictitious MxN PWR Model

Flat Source k-eff: 1.02672

Linear Source k-eff: 1.02708

36 pcm delta
PWR Radial Reflector with Baffle
Flat Source
# Regions: 15392
CPU Sec: 223
K-eff 1.13730

Linear Source
# Regions: 9856
CPU Sec: 405
K-eff 1.13791
Delta = 61 pcm
<table>
<thead>
<tr>
<th>Source Model</th>
<th># Regions Modeled</th>
<th>K-eff</th>
<th>CPU (sec)</th>
<th># Transport Sweeps</th>
<th>Delta pcm from linear src. sol.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td>15392</td>
<td>1.13730</td>
<td>223</td>
<td>10</td>
<td>-61</td>
</tr>
<tr>
<td>Flat</td>
<td>39078</td>
<td>1.13779</td>
<td>1752</td>
<td>16</td>
<td>-12</td>
</tr>
<tr>
<td>Flat</td>
<td>64068</td>
<td>1.13786</td>
<td>6712</td>
<td>27</td>
<td>-5</td>
</tr>
<tr>
<td>Linear</td>
<td>15392</td>
<td>1.13797</td>
<td>392</td>
<td>11</td>
<td>---</td>
</tr>
</tbody>
</table>
Cores 1-12: uniform 2.5 wt% (15x15)
Cores 13-17: Split 3.3 wt% and 2.5 wt% (15x15)
Cores 18-20: Split 3.3 wt% and 2.5 wt% (16x16) C-E Style
Various B4C, AlC, and Gd configurations
**B&W 1810 Criticals**
(with Linear Source MoC)

### Table

<table>
<thead>
<tr>
<th></th>
<th>E7R1 (Flat Src)</th>
<th>J-4.0 (Flat Src)</th>
<th>E7R1 (Lin. Src.)</th>
<th>J-4.0 (Lin. Src.)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ave.</strong></td>
<td>1.00102</td>
<td>1.00079</td>
<td>1.00067</td>
<td>0.99956</td>
</tr>
<tr>
<td><strong>Max-Min</strong></td>
<td>256 pcm</td>
<td>166 pcm</td>
<td>137 pcm</td>
<td>94 pcm</td>
</tr>
<tr>
<td><strong>Std. Dev.</strong></td>
<td>0.00076</td>
<td>0.00049</td>
<td>0.00046</td>
<td>0.00025</td>
</tr>
</tbody>
</table>

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Summary

• A Linear Source (LS) model has been implemented in CASMO5 which improves accuracy and efficiency relative to standard Flat Source MoC
  
  – Factor of 4 faster than FS for equal accuracy, but about 1.5 slower for standard single assembly calculations
  
  – Reduction in storage by a factor of ~10 for fine mesh problems

• The new E7R1 and the JENDL-4.0 data libraries work very well on the B&W criticals and in combination with the linear source model, show good improvements relative to the standard flat source model
## CASMO5 Development Summary:

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Data Libraries</td>
<td>E7R1/JENDL-4.0 ✓</td>
</tr>
<tr>
<td>New 2D Transport Solution</td>
<td>Linear Source Solver ✓</td>
</tr>
<tr>
<td>Updated Absorber Chains</td>
<td>Er, Gd, Hf, AIC, W ✓</td>
</tr>
<tr>
<td>New Depletion Solver</td>
<td>RKF (2nd qrt. 2012)</td>
</tr>
</tbody>
</table>
SSP takes code development seriously!

CASMO5 is not just a collection of methods—it has built into it decades of Studsvik experience in nuclear engineering applications to make a production level lattice physics code.

Validation and verification is underway!